Stacked Two Dimensional Micro-Lens Scanner for Micro Confocal Imaging Array

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ABSTRACT

The concept of Micro Confocal Imaging array is proposed and a stacked two-dimensional microlens scanner has been developed. The 2D raster scanner consists of two 1D scanners fabricated in silicon on insulator wafers stacked perpendicularly. Each scanner has a biconvex surface tension induced polymer microlens. Line scanning ranging 75μm at 4.5kHz and 2D raster scanning over an area of 40μm x 40μm are demonstrated at the focal point of the lens, which is equivalent to a maximum of 11° beam steering.

Keywords: Microlens, Confocal microscope, Scanning, MEMS, Resonator, Lab-on-a-chip

INTRODUCTION

The confocal scanning microscope is a powerful tool for imaging of semitransparent biological samples like cells and tissues because of its non-invasive high resolving power and 3D reconstruction capability [1]. The miniaturization of this confocal microscope will be an enabling technology for quantitative high resolution imaging in many applications such as in-vivo endoscopy, and handheld hypordermic microscopy. Various micromachined optical components such as scanning mirrors, microlenses, and beam splitters are promising candidates for this purpose. In-vivo confocal scanning microscopes with these MEMS components have been demonstrated using an external laser source, a detector, and fiber optic transmission for endoscopy application [2, 3].

However, previously demonstrated MEMS confocal microscopes have not been able to meet the power, volume, and mass constraints for handheld devices because of the massive external components. Integration of a whole confocal microscope including laser sources, intermediate optics, scanners and detectors will enable compact handheld biological imaging systems. Furthermore, an array type integration of multiple MEMS confocal microscopes will play an important role in high-throughput handheld lab-on-a-chip systems as well as in microvision for autonomous microrobots and low mass micro optical imagers for space investigation.

In this paper, we propose the concept of a micro confocal imaging array. The stacked microlens scanner, a key component of the system, has been fabricated and characterized. We describe the design and performance of the stacked microlens scanner.

DESCRIPTION

Micro confocal imaging array

The micro confocal imaging array (μCIA) is an array of fully integrated MEMS confocal scanning microscopes on top of a microfluidic network. The full integration with microfluidic channel allows the development of a highly sensitive optical detector array for lab-on-a-chip systems.

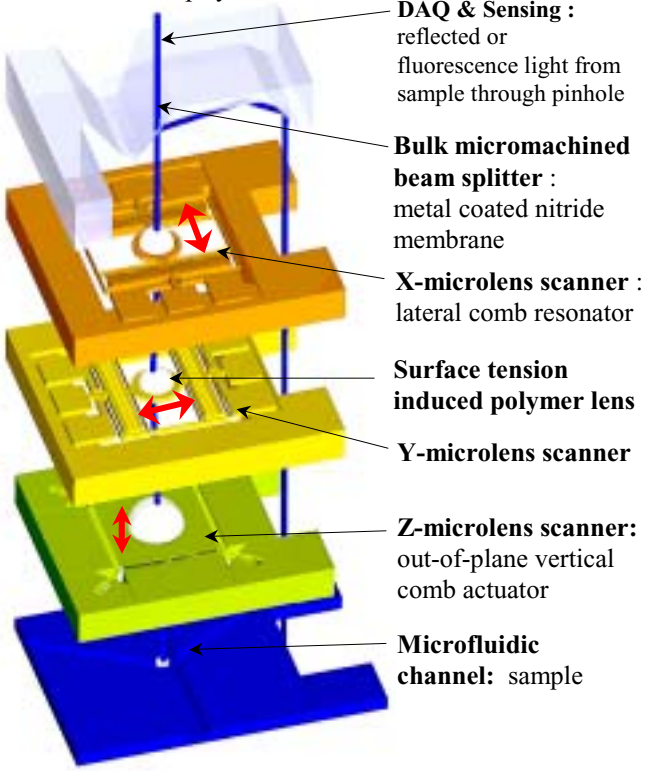

Figure 1: *Schematic of a MEMS confocal microscope unit for the micro confocal imaging array.*

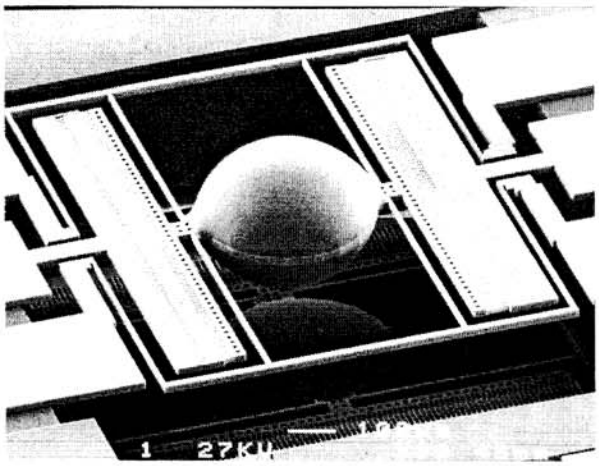

Figure 2: SEM of the stacked 2D microlens scanner.

Figure 1 shows the schematic diagram of one confocal unit of μCIA. The collimated laser light from either a VCSEL or a LED passes through the beam splitter and the 3D scanning module and is focused to a confocal spot inside of the sample. Reflected or fluorescent light returns back by the same optical path and provides intensity information to the detector. This intensity information is highly localized because a detector pinhole discards the out of plane blur and three sequential objective microlenses make focused excitation. 3D raster scanning of a microchannel can be realized by stacking two perpendicular and one vertical comb actuated microlenses. Compared with scanning using micro mirrors, this microlens scanning method has a shorter and simpler light path, which allows the whole microscope unit to fit in a millimeter cube with minimized noise. Since the light path is collimated and normal to each functional layer, the system is modular and the requirement for precise vertical positioning of the optical components is reduced. The following part of this paper describes design and fabrication of the newly developed stacked microlens scanner.

Stacked two dimensional microlens scanner

A stacked two dimensional microlens scanner, the key element of the μCIA, scans the confocal point over the sample to reconstruct a 3D intensity map of the sample with the vertical microlens scanner. Rather than using two 1D mirrors or a 2D mirror, scanning is implemented by orthogonal lateral movement of two trasmissive microlenses. This transmissive scanning not only reduces the complex conventional ray path of the confocal microscope to a simple ray path normal to the substrate but also works as a compound objective. This sequential arrangement can allow higher numerical aperture at a given source to lens distance, which leads to higher axial and lateral resolutions. It also gives smaller spherical aberrations compared with one high

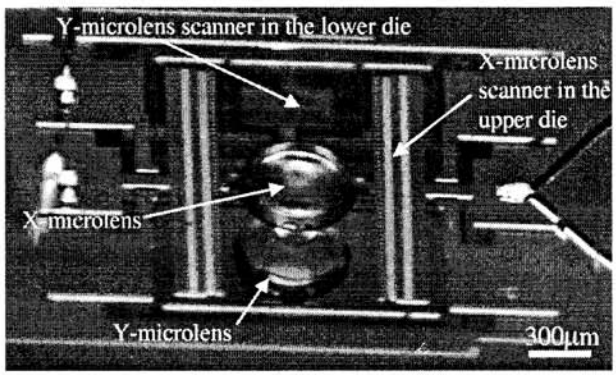

Figure 3: Stereoscopic view of the microlens scanner.

power lens. Also the two independent comb drives with orthogonal lateral orientation and different resonant frequencies can achieve high speed 2D raster scanning without XY cross talk, which is a requirement for confocal scanning microscopy. The cost for this simplicity introduces various optical aberrations such as coma and stigmatism. Figure 2 shows a SEM of the stacked 2D microlens scanner. Thick and thin lenses are vertically aligned and actuators are in the air by backside opened area, which leads to reduce squeeze film damping effect. The open area also works as an optical window for the transmittance lens.

FABRICATION

The stacked microlens scanner is fabricated by following simple steps as shown in Fig. 4. The backside of a silicon on insulator (SOI) wafer is etched down to the buried oxide by deep reactive ion etching (DRIE) to define the optical window. The buried oxide layer is removed by reactive ion etching to prevent membrane explosion in next step. The actuator is defined from the front by DRIE. At this stage structure is ready to test without wet releasing. It is free from squeeze damping and stiction to substrate because the opening area is larger than the moving structure (Fig.2).

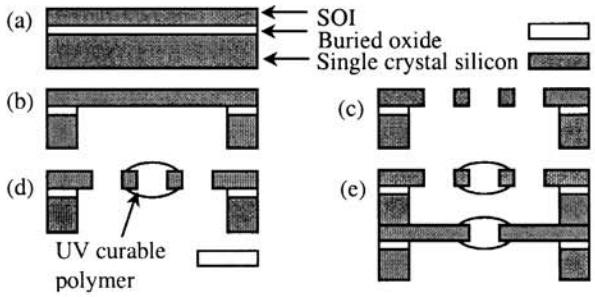

Figure 4: Fabrication process flow: (a) SOI wafer, (b) backside opening, (c) DRIE SOI, (d) lens forming by surface tension, curing by UV exposure, and (e) die align and stacking.

A UV curable polymer droplet is placed manually onto the lens holder using micro manipulators. The liquid polymer is spatially defined by the ring shaped lens holder. Surface tension of the polymer liquid induces a spherical biconvex lens shape. After UV curing of the lenses two dies are aligned, soft-bonded and wire bonded. Figure 3 shows a stereoscopic image of the fabricated device.

RESULT AND DISCUSSION

Scanning speed

The dynamics of the device is characterized using a computer microvision system, a stroboscopic motion analysis system [5]. A microlens scanner is basically an electrostatic comb drive with double folded flexure and a microlens. Flexure width is varied to get two significantly different resonance frequencies to make raster scanning. Figure 5 shows the frequency response of the microlens scanners before and after lens fabrication. Noticeably, the quality factor, Q, increases after lens fabrication, which indicates the damping effect from lens mounting is negligible in the air though the microlens is maximum of 100μm thick. The device is totally in the air by backside opening so that squeeze damping is minimized. The maximum ratio of resonant frequencies is about 6 in this run, which allows only 6 lines scanning resolution for raster scanning. However the device with 3μm flexures can be operated in DC sweeping mode to increase the number of vertical lines.

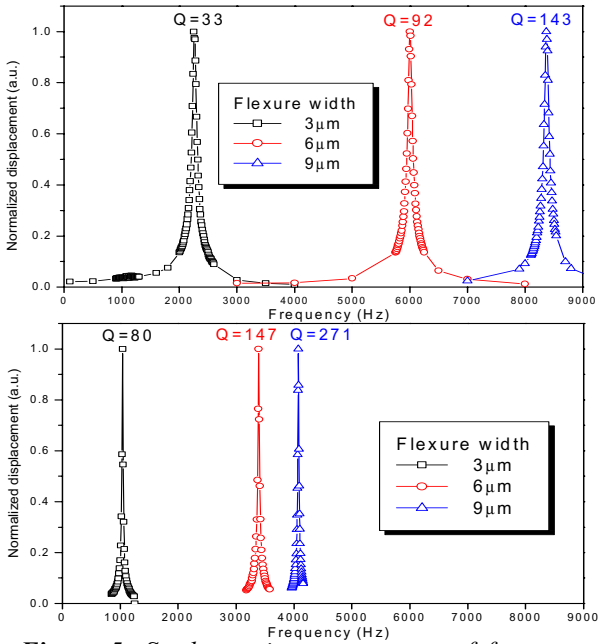

Figure 5: *Stroboscopic measurement of frequency response of the microlens scanners. Q factor increases after lens fabrication: (a) before lens fabrication (b) after lens fabrication*

Scanning range control

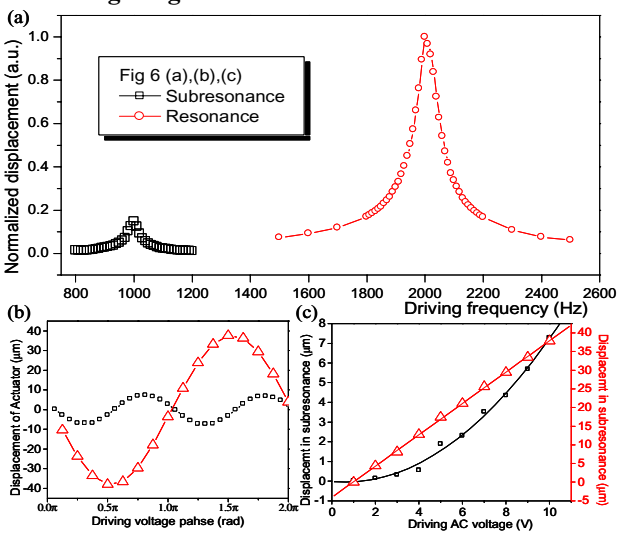

Figure 6: *Comparison of resonance and subresonance mode in terms of scanning range control: (a) frequency response of microlens suttle in resonance and sub resonance, (b) displacent of actuator with repect to driving signal phase, and (c) amplitude modulation in two resonance modes*

Figure 6(a) shows a typical frequency response of the microlens scanner with sub resonance. Because a large signal AC voltage is applied to the structure, the excitation voltage actually contains two harmonics. The electrostatic driving force with biased sinusoidal voltage, F also consists of two harmonics as shown below where n, d, ϵ, h, and V denote the number and gap of comb teeth, dielectric constant of air, thickness of SOI, and applied voltage, respectively.

$$F = \frac{n\varepsilon h}{d}V^2 = \frac{n\varepsilon h}{d}(V_{AC}\cos\omega t + V_{DC})^2 \qquad (1)$$
$$= \frac{n\varepsilon h}{d}\left(\frac{V_{AC}^{\ 2}}{2}\cos 2\omega t + 2V_{DC}V_{AC}\cos\omega t + \frac{V_{AC}^{\ 2}}{2} + V_{DC}^{\ 2}\right)$$

The first sinusoidal term contributes the subresonance and the second term is responsible for resonance of the structure shown in Fig. 6(a). Therefore the actuator actually moves at twice higher frequency in subresonance than driving AC signal, while actuator moves together with driving signal in resonance frequency as shown in Fig. 6(b). Also the maximum displacement varies linearly with driving signal in resonance and proportional to the square of AC voltage in subresonance. Figure 6(c) shows the measured amplitude response in both frequencies. Considering the linearity of the amplitude response in resonant mode, we controlled the scanning range using amplitude modulation of either DC or AC signal at resonance frequency. The maximum scanning range with 10V AC and 6V offset was ±40μm, which is the limit from the comb length, not from instability.

Biconvex polymer microlens

The biconvex polymer lens is fabricated after the SOI actuator is released. One advantage of this lens formation method is the separation of SOI process from the polymer process, which makes the overall process simpler. Because surface tension induces the surface profile, smooth and spherical surface profile is easily achieved. Figure 7 shows an example of the surface profile of the microlens using an interferometric profiler (Wyko™, Veeco Inc.). The fabricated lens has higher numerical aperture and transparency compared with a reflowed photoresist lens. A polymer lens 400μm wide and 84 μm thick results in N.A. of 0.39. This is 2.5 times higher than previous microlens shuttle [6]. The actual pupil of the lens is a hundred micron smaller than the lens diameter so that the spherical aberration is reduced. The focal length of the lens can be controlled by the volume of applied liquid phase polymer using a micro injector.

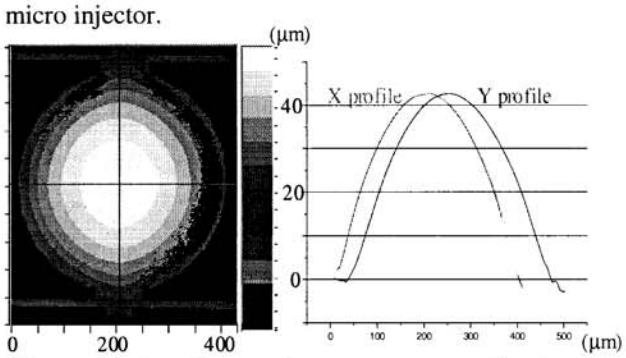

Figure 7: *Interferometric measurement of microlens surface profile.*

Focus scanning

Figure 8 shows line scanning of the lens focus. Large scanning range up to 75μm is achieved at 4.5KHz with a driving AC voltage of 10V with 20V DC bias. Scanning range can be controlled by amplitude modulation of actuation signal. The Q factor was ~140 for this specific device. The scanning angle θ is related with lateral displacement Δd and the focal length of lens f by $\theta=\tan^{-1}(\Delta d / f)$ [4]. The calculated steering angle was 11°. A top view of the 2D scanner is shown in Fig. 9(a). 2D raster scanning of focused source image was

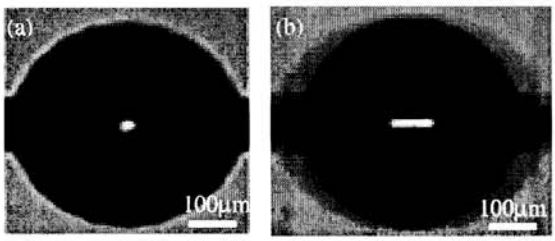

Figure 8: *Line scanning of lens focus:(a) still focal spot and (b) scanner in actuation*

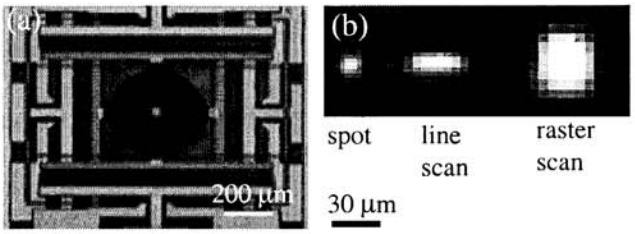

Figure 9: *2D scanning result: (a) top view of 2D scanner, and (b) zoom-in image of focal spot.*

taken under transmittance microscope as shown in Fig. 9(b). The focus images illustrate the following three cases: no movement, X scanning only, and simultaneous XY scanning. Raster scan ranging 40μmx40μm is demonstrated with successful alignment and electrical connection.

CONCLUSION

A stacked 2D microlens scanner has been developed, and is described with the concept of the micro confocal imaging array. Successful fast line and raster scan are demonstrated with linear scanning range control. Precise focal length control of the microlens is under development. Combined with a solid-state laser diode and detector, the microlens scanner can work as a complete confocal imaging system for high throughput lab-on-a-chip systems as well as for quantitative analysis of biomolecular structures for functional genomics and proteomics.

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